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ORIGINAL PAPER

Land-use change and carbon stocks: A case study, Noor County, Iran

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Abstract: Land-use changes and land cover strongly influence carbon stock and distribution within ecosystems. Changing the land-use from natural forest to other land-uses has been more rapid in the past few decades than at any time in Iran's history. In this study, we investigated the effects of changing the land-use from natural forest to other land-uses on carbon stocks in northern Iran. We selected five sites for this study: (I) a natural forest, (II) an agricultural field and (III) plantations of three different species (*Alnus subcordata* .L, *Acer velutinum* .Boiss and *Cupressus sempervirens*). We examined the effects of land-use changes on: (I) soil carbon stock (0–50 cm depth), (II) biomass and carbon content of grassy vegetation and litter and (III) above- and below-ground biomass C in trees. Soil C stock was higher under *A. velutinum* and *C. sempervirens* whereas it was lower under *A. subcordata* and agricultural sites. Biomass and C content of grassy vegetation were significantly higher at *A. velutinum* and *C. sempervirens* plantations. However, litter biomass and C content were significantly higher at the natural forest site. Natural forest had the highest amount of C content in above- and below-ground biomass. Total ecosystem C stocks declined following land-use changes.

Keywords: biomass; climate change mitigation; Hyrcanian forests; plantation; soil organic carbon

Introduction

Land-use change significantly impacts terrestrial ecosystems; it is one of the main factors influencing biodiversity on a global scale (Sala et al. 2000). Land-use change (especially deforestation) has been historically responsible for a large part of the cumulative human-induced greenhouse gas (GHG) emissions (IPCC 2007). Considerable political and socio-economic attention is now focused on understanding and predicting the effects of the coupling between human activities, the biosphere carbon (C) cycle and predicted climate change (Ostle et al. 2009). This coincides with growing scientific evidence that continued atmospheric warming could have important feedbacks on the land's emission and consumption of biogenic greenhouse gas including carbon dioxide (CO_2), methane (CH_4) and nitrous oxide (N_2O) (IPCC 2007). Society and human activities at national and local levels might play a key role in determining GHG feedbacks. In particular, land use and land use change can have significant direct and indirect effects on vegetation cover and soil C stocks by altering the balance between C sequestration and C losses (Ostle et al. 2009). Forests and agricultural lands may play an important role in the overall strategy for slowing the atmospheric accumulation of GHG (Ovando & Caparros 2009).

Changes in vegetation and soil C stocks can occur naturally as ecosystems develop, mature and degrade (Ostle et al. 2009). On the other hand, land-use change is also associated with changes in land cover and C stocks (Bolin & Sukumar 2000). Each soil has an equilibrium C storage potential that is determined by the nature of vegetation, climatic conditions, and physicochemical properties of the soil (Six et al. 2002). An equilibrium in soil organic C (SOC) storage results from a balance between inputs and outputs of C (Fearnside & Barbosa 1998). This equilibrium can be perturbed by land-use change until a new equilibrium is reached in the altered ecosystem. During this process, the soil can act either as a C source or sink, depending on the interaction between land-use, cropping systems, and management practices (Lal 2003; Singh & Lal 2005). The conversion of forest lands to agriculture, as an example, invariably results in the release of large quantities of CO_2 into the atmosphere and rapid decline of SOC stocks (Salinger 2007). Several reviews estimated that loss of soil C after cultivation of native soil ranges from 20-50% (Post & Kwon 2000; Guo & Gifford 2002; Murty et al. 2002; Gregorich et al. 2005).

Land that has been depleted of soil C due to land-use change, however, can be a sink for CO_2 if we can utilize land-use conversion (such as afforestation, reforestation, and restoration of cultivated, abandoned and marginal soils) and management prac-

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tices to increase SOC storage (Silver et al. 2000). Establishment of large-scale short-rotation woody crop plantations has been advocated as an effective method for sequestering CO_2 and mitigating increased atmospheric CO_2 levels (Silver et al. 2000), through increasing long-term C storage in woody biomass (Schimel et al. 2000) and in the soil (Tolbert et al. 2000; Garten 2002), and by providing an alternative source of biomass for bioenergy (Tolbert et al. 2000; Arevalo et al. 2009). However, previous studies on C changes under short-rotation woody crops have been focused on C accumulation in aboveground biomass and/or bulk soil and much remains to be learned on the impact of woody crop plantations on ecosystem C dynamics, particularly in terms of how biomass and soil C storage change with land-use change, and there is much to understand about the effects of land-use change on C stocks.

On a global scale, about 60% of the deforestation in the developing world may be attributable to the advance of agriculture, about 20% to logging (including mining) and 20% to household use of fuel wood (World Bank 1991). In Iran the coverage of regional forests has declined with the expansion of arable land and population growth, economic development, technological advancement, and change in social and political situations (Emadodin 2008). These forests have been reduced from 19 million hectares in the 1950s to 12.4 million hectares in the 1990s (DOE 2003). Over the last 50 years, the area of Iran's farmlands has grown by more than nine times, increasing from 2.6 million hectares to 24.5 million hectares (DOE 2003). Although improvement in the agricultural sector increased productivity greatly during the last 50 years, intensive farming and mismanagement of the deforested areas brought environmental problems and soil impacts such as soil erosion, acidification, soil compaction and pollution (Bahrami et al. 2010).

Land-use changes in Iran have been more rapid in the last 50 years than at any time in Iran's history and are expected to continue at this rate or accelerate in the future (Emadodin 2008). Increase in population and a continuous decline in the area of farmland have led to indiscriminate exploitation of natural forests and fragile lands for agriculture: depletion of soil organic C and nutrients, however, are among the major forms of soil degradation (Khormali et al. 2009; Mojiri et al. 2011). The impact of such land-use change in reducing potential for C storage in woody biomass is also a major concern.

A scientific basis for understanding the role of land-use change in C stocks is crucial to a sustainable management of the land C reservoir. In this study, we aimed to investigate the effects of land-use change from natural forest to other land-uses on C stocks in Noor County in northern Iran. Our results contribute to understanding the effects of land-use change on C stocks (in both soil and biomass) in Hyrcanian forests in the future.

Methods

Study area

This study was conducted in the Chamestan region (36°29' N, 52°7' E) at Noor County in Mazandaran province, in northern Iran. Study sites were located at an elevation of 90 m above sea level with gentle slopes (0–5%). Annual rainfall averages 803 mm, with wetter months occurring between September and February, and a dry season from April to August. Average daily temperatures range from 11.7°C in February to 29.5°C in August. Surface soils are deep, well drained, stone-free, with loam or clay loam texture and acidic pH. Sub-surface soil textures are clay and silt-clay, and are less acidic.

We compared five different land-uses: natural forest, farmland, *Acer velutinum* Boiss plantation, *Alnus subcordata* L plantation and *Cupressus sempervirens* var. *horizontalis* plantation. The natural forest site (approximately 80 years old) included native tree species *Quercus castaneifolia*, *Zelkova carpinifolia*, *Parrotia persica*, *Carpinus betulus*, *Diospyros lotus* and *Buxus hyrcana*. The native forest had been subject to degradation by human activities (such as mismanagement and over-capacity harvesting) for several decades. Approximately 40 years ago some parts of the forest were converted to farmlands by local people for production of rice, and 18 years ago, after clear cutting (in small areas in natural forest), reforestation was undertaken (at 2 × 2 m spacing) with three species, viz *A. subcordata*, *A. velutinum* and *C. sempervirens* (Anonymous 1994). We selected five sites (each with an area of 10 hectares) to study the effects of land-use change on ecosystem C stocks. All sites were adjacent and the soils were developed on the same parent material.

Sampling method

In November 2010, after the end of the growing season, samples and measurements were taken to determine the changes in C stocks after land-use change. Four nested sampling quadrats were established in each land-use type (Fig. 1). Quadrats were of regular shape and of dimensions 10 × 10 m, 5 × 5 m and 0.5 × 0.5 m, and were used, respectively, as the sites for measuring tree biomass, soil sampling, and sampling grassy vegetation biomass and litter (Ponce-Hernandez et al. 2004; Dube et al. 2009). The dimensions of the sampling quadrats coincide with recommended practice in the ecological literature and represent a compromise between recommended practice, accuracy and practical considerations of time and effort (Ponce-Hernandez et al. 2004). The design of nested quadrats of different sizes met requirements for measuring vegetation of different sizes and strata, and for collecting debris and litter for estimation of biomass (Ponce-Hernandez et al. 2004). In 10 × 10 m quadrats, we measured all trees, recording tree height (H), diameter at breast height (DBH), diameter of canopy or crown in two perpendicular directions (for convenience, "length" (L) and "width" (W)), height to the base of the crown (Hc) and percentage of foliage cover in the crown or canopy (Fc). After removing litter and grassy vegetation, soil samples were taken in four replicates: from four corners of square 5 × 5 m plots. Samples were taken at 0–15 cm, 15–30 cm and 30–50 cm depths (with a hand trowel, sampling uniformly at each depth) and mixed to form a composite sample for each depth. Twelve soil samples were collected in every land-use, one for each of three soil depths at each of four quadrat corners.

Samples of grassy vegetation and litter were taken from 0.5 × 0.5 m quadrats and transported to the laboratory in plastic bags. There were no shrubs on the study sites.

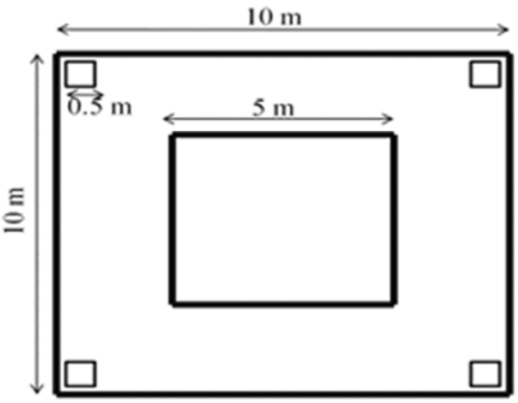

Fig. 1 Sampling plots schema

Soil organic carbon

We assumed that soils on all five land-uses were similar before the imposition of land-use changes. We also assumed that soil C levels at the natural forest site reflected a balance between C inputs and losses while those at plantations and farmlands reflect changes in this balance brought about by land-use change. Soil samples were air-dried and sieved (2 mm mesh) for laboratory analyses. Bulk density was determined by the excavation method for each soil depth (Bahrami et al. 2010). To determine SOC, we used the Walkley-Black oxidation method (Allison 1975). We used the averages of soil bulk density and SOC concentration for analyses. The total stock (C_S g/cm^2) of SOC at each soil depth was calculated by Equation 1 (Guo & Gifford 2002; Chen & Li 2003):

$$Cs = BD \times C \times D \tag{1}$$

where *BD* is the soil bulk density (g/cm^3) at each soil depth, *C* is the SOC concentration (%), and *D* is the soil sampling depth (cm). The values obtained were used to calculate the soil C stock per hectare.

Carbon content of grassy vegetation and litter

To obtain the above-ground grass biomass, we manually harvested vegetation from 0.5 × 0.5 m quadrats. Then, the fresh biomass was dried at 65°C for five days and weighed once again to obtain dry biomass. To measure below-ground biomass, the greatest quantity of roots growing under each plot was carefully extracted, cleaned and washed in slowly running water to remove soil from roots, and then dried at 65°C for five days and weighed. The values obtained were used to calculate the total grassy vegetation biomass per hectare. Litter samples were also collected from the 0.5 × 0.5 m quadrats and oven-dried at 65°C until weights stabilized and then weighed. Biomass C content of ground vegetation and litter were calculated by multiplying the dry mass by a standard factor of 0.5 (IPCC 2001; Pregitzer & Euskirchen 2004; Fitzsimmons et al. 2004; Arevalo et al. 2009; Dube et al. 2009). Then, the resulting C values were converted to tons per hectare.

Biomass C estimation

Tree's biomass was estimated separately for above- and below-ground in natural forest and forest plantation sites, and then the total biomass was estimated for each site. To estimate the above-ground tree biomass we used the allometric method of Ponce-Hernandez et al. (2004). For methodological convenience, the biomass calculations for trees were segregated according to tree morphology: (I) stem, (II) crown. To calculate stem biomass, the basal area was first estimated using Equation 2:

$$A_b = \pi \times r^2 \tag{2}$$

where A_b is tree basal area, π = 3.145927, and *r* is the radius of the tree at breast height (0.5 DBH). Then the stem volume (V) of each tree was calculated using Equation 3:

$$V = A_b \times H \times Kc \tag{3}$$

where A_b is tree basal area, H is tree height and K_c is a site-dependent constant in standard cubing practice used in forest inventory. To calculate crown volume (V), we used Equation 4 for coniferous species and Equation 5 for broadleaf species:

$$V = \pi \times \frac{Db^2 \times Hc}{12} \tag{4}$$

$$V = \frac{\pi \times Db^2}{12} \tag{5}$$

where, π = 3.141592, *Db* = diameter of the crown ((L+W)/2) and *Hc* = height from the ground to the base of the crown. The volume of the crown estimated by these equations is the gross total volume. In reality, much of this volume is empty space. The actual proportion of the volume occupied by branches and foliage was estimated by standing beneath the canopy or crown, beside the trunk, and obtaining a careful visual appreciation of the canopy structure. This proportion is then used to discount the air space in the crown volume:

Solid volume = V × proportion of branches and foliage in crown volume

Biomass (stem and crown) in kilograms was calculated by multiplying by the wood density (WD) corresponding to each tree species estimated using Equation 6:

$$\text{Biomass} = V \times WD \times 1000 \tag{6}$$

Total aboveground biomass was estimated as:

Total aboveground biomass = Stem Biomass + Crown Biomass

Because of the high cost of sampling and measuring roots, we used non-destructive methods (such as allometric equations) to assess below-ground biomass. On the other hand, it is recommended that in situations where no empirical equation exists, the root volume and biomass should be estimated as a fraction of the aboveground biomass, as an interim measure, to estimate total biomass (Ponce-Hernandez et al. 2004). Therefore, relationships recommended by Ponce-Hernandez et al. (2004) were used to estimate below-ground biomass:

For coniferous species: Belowground biomass = 0.25 Aboveground biomass

For broadleaf species: Belowground biomass = 0.30 Aboveground biomass

These values were converted to tons per hectare and then calculation of C stock as biomass involved multiplying the total biomass by a conversion factor that represents the average C content in biomass. It was not practicable to separate the different biomass components to account for variations in C content as a function of the biomass component. Therefore, we assumed C to be equal to 50% of calculated biomass (Fitzimmons et al. 2004; Redondo-Brenes & Montagnini 2006; Dube et al. 2009): C = 0.5 × Biomass (total)

Total C stock

Total C stock of each quadrat was estimated using Equation 7:

$$C_T = C_S + C_V + C_L + C_B \tag{7}$$

where C_T is total C stock in each quadrat, C_S is total soil C stock (depths of 0–50 cm), C_V is C content of grassy vegetation, C_L is C content of litters, and C_B is total C content in biomass. These values were converted to tons per hectare for each land-use type.

Statistical analyses

The influence of land-use on grassy vegetation, litter and above- and below-ground biomass C stocks were tested using one-way analysis of variance (ANOVA) with PROC GLM in SPSS17. The assumption of normality was assessed using the univariate procedure in SPSS with a Kolmogorov-Smirnov test. All data conformed to a normal distribution. Attending to the normality and variance homogeneity of data, Two-way analyses of variance (ANOVA) using PROC GLM were used to compare soil C stocks between experimental sites. Duncan's Test was used to identify and separate significant main and interaction effects.

Results

SOC

A. velutinum and *A. subcordata* plantations had the highest and *C. sempervirens* the lowest C concentration (%) in the 0–15 cm soil layer (Table 1). Bulk density in farmlands was the lowest of the studied land-use types in the 0–15 cm soil layer and the highest was in the *C. sempervirens* plantation. In the 0–15 cm soil depth, the amount of C stock was highest in *A. velutinum* and *C. sempervirens* plantations and lowest in farmland (Table 1).

Table 1. Soil C stock in three different depths under different land-uses

Land uses	Soil depths																	
	0–15 (cm)						15–30 (cm)						30–50 (cm)					
	Organic C (%)		Bulk density (g·cm^{-3})		Carbon stock (t·ha^{-1})		Organic C (%)		Bulk density (g/cm^3)		Carbon stock (t·ha^{-1})		Organic C (%)		Bulk density (g·cm^{-3})		Carbon stock (t·ha^{-1})	
Natural forest	1.2ab	-0.02	1.9ab	-0.24	36.6ab	-3.85	0.8b	-0.11	1.91 b	-0.13	25.66b	-4.95	1.14ab	-0.05	2.59ab	-0.5	58.4ab	-10.4
A. velutinum	1.34 a	-0.03	2.28 a	-0.25	46.2 a	-5.32	1.22 a	-0.06	2.1 b	-0.17	38.87 b	-1.73	0.97 b	-0.1	3.6 a	-0.31	71.22 a	-12.01
A. subcordata	1.33a	-0.003	1.72ab	-0.13	34.56ab	-2.66	1.17 a	-0.05	1.77 b	-0.1	31 b	-0.94	0.93 b	-0.13	1.88 b	-0.18	35.05 b	-6.74
C. sempervirens	1.22 b	-0.04	2.36 a	-0.29	42.65 a	-4.05	1.18 a	-0.05	3.06 a	-0.44	54.73a	-9.71	0.88 b	-0.12	3.03a	-0.48	54.47ab	-13.48
Agricultural field	1.3ab	-0.03	1.44 b	-0.08	28.18 b	-1.06	1.33 a	-0.03	1.45 b	-0.07	29.1b	-1.34	1.3a	-0.01	1.58b	-0.02	41.19ab	-0.59
ANOVA	*		*		*		**		**		**		*		**		*	

a- ANOVA results: Mean values with the same letter among different land-uses do not differ significantly with each other. *, **- respectively show the significant at the 0.05 and .001 level.

In the 15–30 cm soil layer, soil C concentration (%) under natural forest was significantly lower than in other land-use types. Bulk density and soil C stock in this soil layer were significantly higher under *C. sempervirens* plantation than at other sites (Table 1). Farmland had the highest C concentration (%) in the 30–50 cm soil layer and soil bulk density was higher under *A. velutinum* and *C. sempervirens* plantations compared than at other sites. Soil C stock under *A. velutinum* plantation was higher than other land-use types at the 30–50 cm soil depth (Table 1).

Analysis of variance showed that land-use and soil depth significantly influenced all studied factors (SOC concentration (%), bulk density and C stock) (Table 2), while the interactive effect of land-use type and soil depth was significant only in relation to SOC (%).

Soil depth significantly affected SOC (%) at all land-use types except for farmland. SOC concentrations decreased with increasing soil depth in all cases except natural forest. Bulk density at the *A. velutinum* plantation varied significantly with soil depth,

whereas at other land-use types the differences were not significant. The effect of soil depth on C stock was significant under natural forest, *A. velutinum* and farmland, but not significant under *A. subcordata* and *C. sempervirens* plantations (Fig. 2).

Table 2. ANOVA for soil C stock at three depths with the interactive effects of land-use and depth

	Land-use	Depth	Land-use × Depth	Error
Degrees of freedom	4	2	8	45
Organic C (%)	0.096**	0.322**	0.075**	0.02
Bulk density (g/cm^3)	3.822**	1.98**	0.486	0.298
Carbon stock (t/ha)	1004.36**	1579.42**	276.6	179.46

Note: ** show the significant at the 0.001 level.

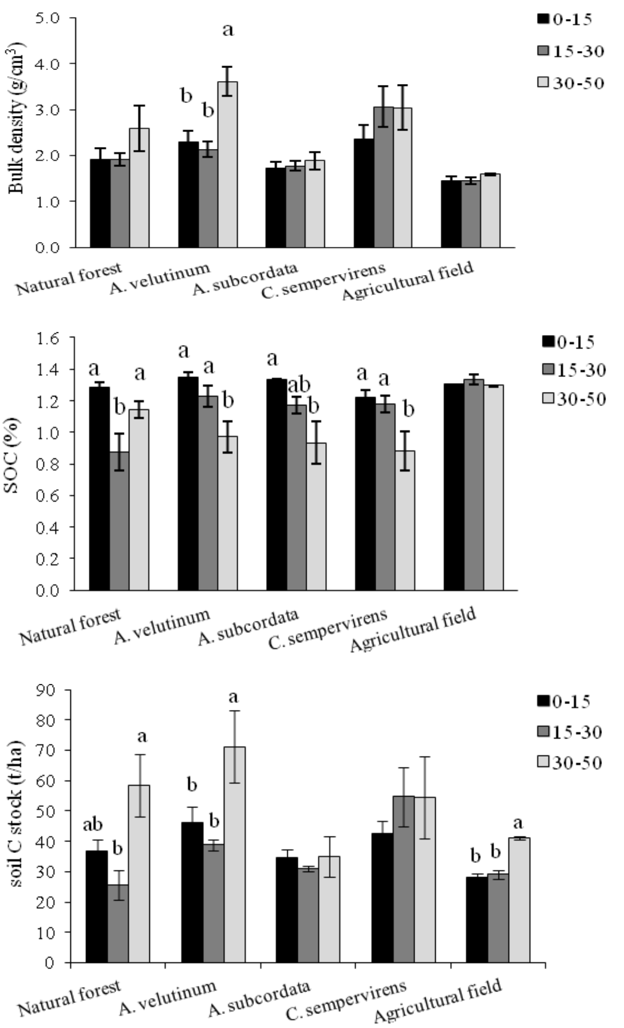

Fig. 2 Influence of soil depth on SOC (%), bulk density, and C stock under five different land-use types.

Across the 0−50 cm soil depth range, *A. subcordata* and agricultural sites had the lowest and *A. velutinum* and *C. sempervirens* the highest amount of C stock (Fig. 3). Assuming that the SOC stock of the natural forest site was equivalent to that of the plantation sites and farmland before the land-use changes, we conclude that the soil C stock increased under *A. velutinum* (35.47 t·ha^{-1}) and *C. sempervirens* (31.06 t·ha^{-1}) and decreased under *A. subcordata* (20.2 t·ha^{-1}) during the 18-year period after the land-use change. Forty years after the land-use change, soil C stock declined under farmland (at a rate of 0.56 t·ha^{-1}·a^{-1}). The rates of increase in soil C stock under *A. velutinum* and *C. sempervirens* (after land-use change from natural forest to plantation) were about 1.97 and 1.72 (t·ha^{-1}·a^{-1}), respectively. Also the rate of reduction of soil C stock was 1.12 (t/ha/year) under *A. subcordata* plantation.

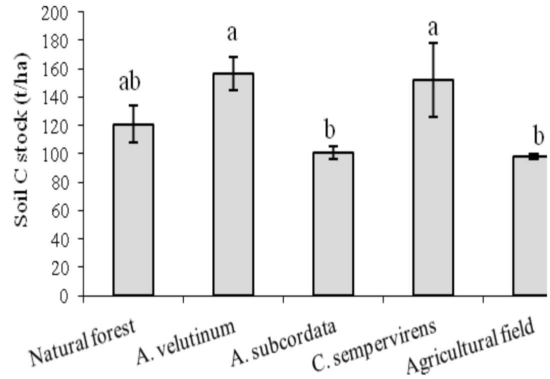

Fig. 3 Soil C stock (0−50 cm depth) under different land-uses

C content of grassy vegetation and litters

Biomass and C content of grassy vegetation was significantly higher under *A. velutinum* and *C. sempervirens* plantations that for other land-use types. However, litter biomass and C content were significantly higher under natural forest (Table 3).

Table 3. Biomass and carbon content (mean ± standard error) in grassy vegetation and litter under different land-uses

Land use	Vegetation Biomass (t·ha^{-1})	Vegetation C content (t·ha^{-1})	Litter Biomass (t·ha^{-1})	Litter C content (t·ha^{-1})
Natural forest	0.64 b -0.168	0.32 b -0.08	4.34 a -0.92	2.17 a -0.45
A. velutinum	4.97 a -2.2	2.4 a -1.1	2.38 b -0.32	1.19 b -0.16
A. subcordata	0.85 b -0.122	0.42 b -0.06	1.26 b -0.22	0.63 b -0.11
C. sempervirens	4.34 a -0.3	2.17 a -0.15	2.23 b -0.74	1.11 b -0.37
Agricultural field	0.98 b -0.12	0.492 b -0.062	-	-
ANOVA	*	*	*	*

- ANOVA results: Mean values with the same letter among different land-uses do not differ significantly with each other. *- show the significant at the 0.05 level.

Biomass C content

Significant differences were observed in above- and below-ground biomass and biomass C content between natural forest and plantation sites. Biomass (both above- and below-ground) and biomass C stock of natural forest was significantly higher

than for plantation sites in the following order: natural forest > *A. subcordata* > *A. velutinum* > *C. sempervirens*. The rates of C storage in the biomass of plantations were about 21.47, 23.41 and 11.27 ($t·ha^{-1}·a^{-1}$) for *A. velutinum*, *A. subcordata* and *C. sempervirens,* respectively. This rate was about 7.78 ($t·ha^{-1}·a^{-1}$) in natural forest.

Total C stock

Total ecosystem C stock (vegetation, litter and biomass C plus SOC) at 0–50 cm soil depth was significantly affected by land-use change (Fig. 5). Total ecosystem C stock ranged from 98.97 ($t·ha^{-1}$) to 753.45 ($t·ha^{-1}$) in the following order: natural forest > *A. velutinum* > *A. subcordata* > *C. sempervirens* > farmland.

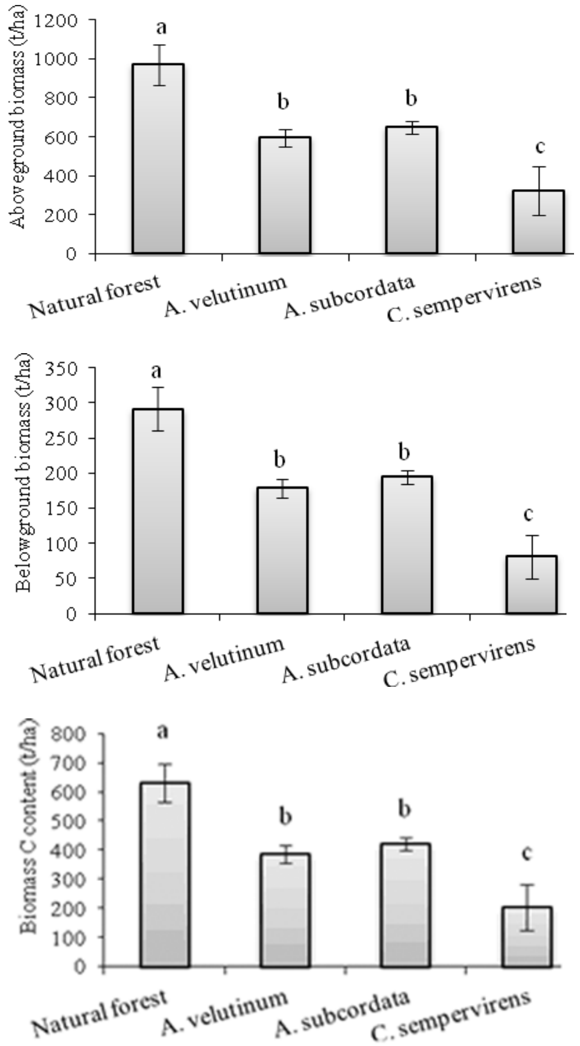

Fig. 4 Above and belowground biomass and C content of biomass in natural forest and forest plantation sites.

C stocks of grassy vegetation and litter were inconsiderable compared to those in biomass and soil. In natural forest and forest plantations a large proportion (> 50%) of total ecosystem C was stored in the biomass but farmland had no tree biomass and soil stored the largest amount of C (Fig. 6).

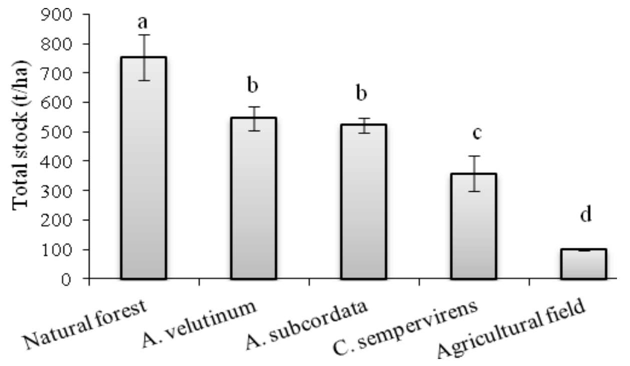

Fig. 5 Total C stock under different land-uses.

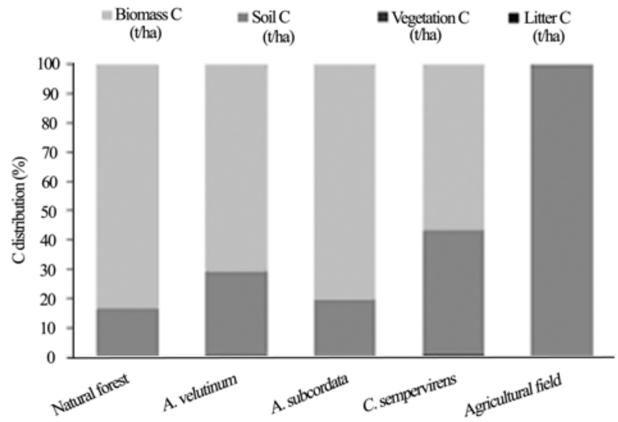

Fig. 6 Ecosystem distribution of C under different land-uses.

Discussion

Effects of land-use change on SOC

A basic assumption for this experiment is that the soil properties of the five studied land-use types (farmland, three different species plantations and natural forest) were similar prior to the imposition of land-use changes. Given that all sites were under the same land-use (natural forest) before land-use change and were adjacent and located on generally flat topography, we are confident in this assumption.

Soil C stock differed significantly between land-use types at all three soil depths. As shown in Fig. 3, across the 0–50 cm soil depth range, the change of land-use from natural forest to *A. velutinum* and *C. sempervirens* plantations increased soil C stock (35.47 $t·ha^{-1}$ and 31.06 $t·ha^{-1}$, respectively), while the changes to *A. subcordata* plantation and farmland reduced soil C stock (20.2 t/ha and 22.32 $t·ha^{-1}$, respectively). After conversion of natural forest to plantations, there were reduced inputs of C into the soil from the prior land-use, combined with accelerated decomposi-

tion of soil organic matter as a result of disturbance, and this led to a net loss of SOC, as reported for other sites by Turner et al. (2005) and Richards et al. (2007). The accumulation of litter in the humus layer and the lack of mixing of the surface litter material with the mineral soil resulted in the low C stocks in the mineral soil at the natural forest site, as reported by Arevalo et al. (2009). In forest environments, SOC inputs come in part from aboveground litterfall that accumulates on the soil surface. Fallen leaves decompose partially on the soil surface before being incorporated into the soil, resulting in less accumulation of SOC and a thinner A horizon (Paul et al. 2002). Arevalo et al. (2009) suggested that soil C loss in the early stages of plantation development might be due to lower input than output of organic C. In some systems, this loss of SOC is not balanced until 5−10 years after planting and on some sites, a reduction in SOC might persist until the end of the rotation. The patterns of accumulation and loss of C vary according to location, soil type, tree species and plantation management system (Turner et al. 2005). We conclude that under *A. velutinum* and *C. sempervirens* plantations, after conversion for 18 years, SOC was balanced and then even increased in comparison to the natural forest site. Under *A. subcordata* plantation, achievement of a balance of SOC will probably require a longer time period. Arevalo et al. (2009) also reported early soil C loss under young poplar plantations followed by increased SOC stock with plantation age, so we expect an increase in soil C stock with increasing age of the plantations.

On the other hand, differences of soil C stock between land-use types could be due to the distinct quality of plant material (which led to different C concentrations) as well as to significant differences between soil bulk densities under different land-uses (Dube et al. 2009; Varamesh et al. 2009).

Conversion of natural forest to farmland is usually followed by a decrease in SOC stocks (Guo & Gifford 2002). We observed this result after conversion of natural forest to farmland but the reduction in SOC was not statistically significant. Murty et al. (2002) reported that 20%–30% of incipient SOC stocks were lost in the first few years due to cultivation and losses continued at a slower rate until reaching a new equilibrium after 30−50 years. From this study, it emerged that 40 years of conventional agricultural use of a natural forest soil resulted only in a slight and non-significant reduction of SOC stocks in the top 50 cm of soil. Previous studies suggested that this reduction might be due to (I) lower inputs of organic matter, (II) changes in soil microclimates that increase rates of organic matter decomposition, (III) increase in decomposability of crop residues due to changed litter quality (for example, lowered C:N ratio and lignin content), and (IV) tillage-induced disturbances that decrease soil aggregation and physical protection of soil organic matter (Lal 2005; Post & Kwon 2000). Arevalo et al. (2009) also reported non-significant reduction of SOC 80 years after land-use change from native aspen forest to farmland. Several reviews (Post & Kwon 2000; Guo & Gifford 2002; Murty et al. 2002; Gregorich et al. 2005) estimated that loss of soil C after cultivation of native soil ranges from 20%−50%. Davidson & Ackerman (1993) suggested that nearly all C lost from soil occurs within 20 years, and that most occurs within 5 years after initial cultivation.

The rate of reduction of soil C storage after land-use change to farmland was about 0.56 $t{\cdot}ha^{-1}{\cdot}a^{-1}$. The rates of increase in soil C stock under *A. velutinum* and *C. sempervirens* plantations were about 1.97 and 1.72 $t{\cdot}ha^{-1}{\cdot}a^{-1}$, respectively. The rate of reduction of soil C storage was 1.12 $t{\cdot}ha^{-1}{\cdot}a^{-1}$ under *A. subcordata* plantation. The rates of C storage, and volume and quality of C stock are closely related to action and reaction between climate, soil, tree species, management and chemical composition of litter (Varamesh et al. 2009; Arevalo et al. 2009) and vary between different land-use types at different locations.

Fig. 2 shows that under plantation sites, SOC concentrations declined with increasing soil depth. Varamesh et al. (2009) interpreted the same results as a gradual process of litter decomposition and conversion to humus that starts from the soil surface. Under natural forest at 30−50 cm soil depth, we recorded higher SOC concentration than at 15−30 cm soil depth. This can be explained by the loss of SOC due to erosion. Varamesh et al. (2009) concluded that the concentration of organic C at different soil depths depends on the amount of humus, canopy coverage, and vegetation species. On farmland, SOC concentration did not vary significantly by soil depth. We suggest this is because of the plowing and mixing of soil layers with crop residues and humus. On the other hand, the 30−50 cm soil layer had the highest amount of soil C stock of all land-use types and we attribute this to the high bulk density in this soil layer. Previous studies reported that about 60% of SOC is stored in topsoil layers (Woomer & Sall 2004, Varamesh et al. 2009, Arevalo et al. 2009).

C content of grassy vegetation and litter

Forest ground vegetation biomass is generally highly variable, depending on forest management, stand-specific canopy coverage and soil conditions, which affect light, water and nutrient availability for the development of ground vegetation (Peichl & Arain 2006). Grassy vegetation biomass and C storage were highest at *A. velutinum* and *C. sempervirens* plantations, due to their relatively dense understory of grasses. *A. subcordata* plantation had lower C storage in grassy vegetation than other plantation sites, probably due to the extensive crowns of trees. Peichl & Arain (2006) observed an increase in ground vegetation biomass and C storage with increasing plantation age. Natural forest had the lowest C content in grassy vegetation due to its thick litter layer on the forest floor, which constrained the growth of grasses. Farmland was harvested before our sampling and therefore had less grassy vegetation compared to plantation sites. Natural forest had greater C storage in litter than did plantations. We conclude that was because of greater litter production due to the older age of the natural forest. It can also be attributed to slower litter decomposition under natural forest (due to characteristics of the dominant forest species).

Biomass C storage in natural forest and forest plantation sites

Biomass C storage was significantly higher in natural forest and, among plantations, was lowest at the *C. sempervirens* plantation. The rate of increase of biomass C at plantation sites took the

following order: *A. subcordata* > *A. velutinum* > *C. sempervirens* (with biomass C accumulation rates of 23.41, 21.47 and 11.27 $t{\cdot}ha^{-1}{\cdot}a^{-1}$, respectively). Other studies reported different rates of C storage in biomass for different species. Arevalo et al. (2009) reported a rate of 6.3 $t{\cdot}ha^{-1}{\cdot}a^{-1}$C for a hybrid poplar plantation in north central Alberta, Canada. We estimated biomass C accumulation at about 7.78 $t{\cdot}ha^{-1}{\cdot}a^{-1}$ in natural forest but this rate was probably affected by human activities such as mismanagement and over-harvesting. C stock in biomass and biomass production obviously depend on species growth potential, environmental conditions (such as weather and soil), site management (such as pruning and thinning), and other factors. Each species in each site condition will show different rates of C accumulation in biomass. We found that *A. subcordata* and *A. velutinum* had high levels of C stock in biomass, whereas *C. sempervirens* had the lowest stock of C in biomass, possibly due to the lower tree survival and density at this site. Our findings reveal the need for continued monitoring of plantations to improve the management prescriptions for the studied species. Where there has been appropriate species-site matching and when management prescriptions are effective, plantations usually remain healthy and productive.

Total ecosystem C stock and distribution under different land-uses

Land-use change from natural forest to farmland and plantation significantly reduced ecosystem C stocks (Fig. 5). Previous research concluded that forest ecosystems had more C stock (above- and below-ground biomass plus SOC) compared to other land-uses such as pasture and farming (Fitzsimmons et al. 2004; Arevalo et al. 2009). Fitzsimmons et al. (2004) reported 158 $t{\cdot}ha^{-1}$ C for forest stands, 63 $t{\cdot}ha^{-1}$ C for pasture, and 81 $t{\cdot}ha^{-1}$ C for cultivated sites in central Saskatchewan, Canada. The basic ways in which forest and agricultural lands can directly or indirectly contribute to GHG mitigation are the conversion of non-forest lands to forest, preserving and increasing C in existing forest and agricultural soils, growing biomass to substitute fossil fuel-based products and altering agricultural and forestry fossil fuel usage patterns (Ovando & Caparros 2009).

Differences in ecosystem C storage between different land-uses have been attributed to differences in biomass (Fitzsimmons et al. 2004; Arevalo et al. 2009). In our results, differences in total C stocks by land-use type resulted from differences in both soil and biomass C storage. In natural forest and forest plantations, most (> 50%) of the ecosystem C stock was stored in biomass, while C storage in grassy vegetation and litter was inconsiderable. Arevalo et al. (2009) reported that SOC content (0–50 cm soil depth) was greater than biomass C for all land-use types (agriculture, 2-year-old hybrid poplar plantation, 9-year-old hybrid poplar plantation, grassland and native aspen forest). They concluded that ground vegetation must be assessed in determining C stock for land-use and land cover changes because the ground vegetation biomass contained a sizeable fraction of the total ecosystem C stock.

Conclusion

Land-use changes, cultivation and plantation significantly affected total ecosystem C storage although management-induced differences in C stocks were confined to differences in above- and below-ground biomass C storage. Changing the land-use from natural forest to *A. velutinum* and *C. sempervirens* plantations improved soil C stock, and conversion of natural forest to *A. subcordata* plantation and farmland had a negative effect on soil C storage. Our results showed that C was storage in grassy vegetation and litter was inconsiderable compared to that in other components of ecosystems (soil and biomass). Our study also indicates that in natural forest and forest plantation sites, large amounts of C were stored in above- and below-ground biomass. Therefore, management opportunities for increasing biomass can be beneficial for GHG mitigation. Also we recommend agroforestry systems to increase biomass on farmlands and thereby for increasing total ecosystem C stocks.

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